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RESEARCH MEMORANDUM

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Air Materiel Command, U. S. Air Force

COOLANT-FLOW CALIBRATIONS OF THREE SIMULATED POROUS GAS-TURBINE BLADES

By Jack B. Esgar and Alfred L. Lea

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation was conducted at the NACA Lewis laboratory to determine whether simulated porous gas-turbine blades fabricated by the Eaton Manufacturing Company of Cleveland, Ohio would be satisfactory with respect to coolant flow for application in gas-turbine engines. These blades simulated porous turbine blades by forcing the cooling air onto the blade surface through a large number of chordwise openings or slits between laminations of sheet metal or wire. This type of surface has a finite number of openings, whereas a porous surface has an almost infinite number of smaller openings for the coolant flow.

The investigation showed that a blade made of sheet-metal laminations stacked on a support member that passed up through the coolant passage was completely unsatisfactory because of extremely poor coolant flow distribution over the blade surface. The flow distribution for two wire-wound blades was more uniform, but the pressure drop between the coolant supply pressure and the local pressure on the outside of the blades was too low by a factor ranging from 3 to $3\frac{1}{2}$ for the required coolant flow rates. The pressure drop could be increased by forcing the wires closer together during blade fabrication.

INTRODUCTION

Transpiration cooling is shown in reference 1 to be the most effective method of air cooling gas-turbine blades. The tensile strengths of porous metals fabricated by powder metallurgy, however, are too low for use in present production-type rotor blades. The fabrication of simulated porous blades as a possible solution to this problem has been presented by the Eaton Manufacturing Company of Cleveland, Ohio. The Eaton Company suggested that the simulated porous shell could be fabricated

from stamped sheet-metal laminations that would be attached to a support member extending through the coolant passage, or that the support member could be wound with wire. The cooling air would be forced through the laminations or between adjacent layers of wire forming a cool film of air over the blade surface. The support member used in their blades was suggested by personnel of the NACA Lewis laboratory.

In order to determine whether the coolant flow could be properly distributed through this type of blade construction, three configurations fabricated by the Eaton Manufacturing Company were flow-tested at Lewis laboratory and the results are presented herein.

SYMBOLS

The following symbols are used in this report:

A	blade surface area
C	constant
g	acceleration due to gravity
p	pressure
R	gas constant
T	temperature
w	weight flow per unit time
α,β	constants in equation (2)
μ	absolute viscosity
τ	thickness

Subscripts:

a	cooling air
i	inside blade surface
o	outside blade surface

APPARATUS

Blade Descriptions

The blades simulated porous turbine blades by forcing cooling air onto the blade surface through a large number of chordwise openings or slits between laminations of sheet metal or wire in the blade wall. This type of surface has a finite number of openings, whereas a porous surface has an almost infinite number of smaller openings for the coolant to pass through. An attempt was made to obtain a blanket of air similar to that of a transpiration-cooled surface by placing the slits sufficiently close together. This cooling process differs from film cooling in that the slits for film cooling would lie in a radial direction on the blade surface so that the air would spill back across the band of metal between slots.

Sheet-metal laminated blade. - This blade was made from laminations of sheet steel 0.010-inch thick forced down over a finned support member; it is shown partially assembled in figure 1. The laminations were made by a stamping machine from sheet stock and were given a "dish" similar to that of a Belleville spring. The laminations were dished because (1) the local flow rates might possibly be controlled by varying the amount of dishing at local positions around the blade perimeter; (2) the strength of the laminations would be improved; and (3) centrifugal forces would tend to flatten the laminations and cause them to dig into the fins on the support member, thus holding the laminations in place more securely.

The support member was machined integral with the blade base and was of a tapered cross section to reduce root stresses. Constant cross-sectional fins were machined onto the tapered part of the support member to provide a means of attaching the laminations and to provide cooling-air passages. Although brazing or welding methods of attaching the laminations to the fins had been considered, only a light force fit was used for attaching the laminations in the blade investigated.

Wire-wound blades. - Air-flow calibrations were made on two wire-wound blade shells shown in figure 2. These blade shells were fabricated only for flow tests; consequently, a simple nontapered support member similar to that shown in figure 1, but without a base, was used. The blades were made from wire having two different cross sections as shown in figure 2(a). The wire for one blade was keystoned and knurled in an effort to provide a controlled flow rate between adjacent wires on the blade. The amount of knurling on the sharp edge of the keystone was varied to provide a possible method of obtaining the correct relation

between coolant supply and discharge pressures. The wire for the other blade was rectangular in cross section. The blade with the knurled wire also had a plate attached to the blade base, which contained small metering orifices to control the local flow rates to the various parts of the blade (fig. 2(c)).

An exploded view of the knurled blade showing the base attachment for the flow calibration is presented in figure 3. The plate with the two slots was used to make the cooling-air flow path similar to that of an actual blade. The slots were the same as those at the root of the sheet-metal laminated blade.

Flow-Calibration Apparatus

Both the total coolant flow rate through the entire blade and the local flow rate on the concave and convex surfaces were measured in this investigation. A schematic sketch of the apparatus is shown in figure 4. The total flow through the blades was measured by means of rotameters installed in the line between the supply line and the blade. The air was supplied through the laboratory service air system at a pressure of 120 pounds per square inch. The air was filtered to remove dirt and oil, and the pressure was reduced to the proper operating pressure by means of a pressure regulator. The flow through the blade was adjusted by means of a needle valve between the rotameters and the blade. The cooling air discharged through the blade to the atmosphere.

Local coolant flow rates were measured by means of a sampling probe 1/2 inch in diameter that was contoured to fit the blade surface and was connected to the laboratory altitude exhaust system. The flow through the sampling tube was measured by means of a rotameter. In order to be sure that the flow through the blade into the sampling tube was the same as if the tube were not placed against the blade surface, the pressure in the tube was adjusted until it was exactly atmospheric, that is, until the manometer connected to the probe showed a zero differential pressure.

Figure 5 shows the sampling tube being held up to the sheet-metal laminated blade during the flow investigation; the jig used to hold the laminated blade is also shown. The set-screw arrangement at the top of the blade was used in an effort to vary the local flow rates around the blade periphery by adjusting the pressure on top of the laminations.

RESULTS AND DISCUSSION

Flow Results of Sheet-Metal Laminated Blade

A calibration run of the coolant flow rates for this blade was not made because the preliminary tests showed that almost all of the cooling air passed through the concave surface of the blade making it impossible to measure any flow with the sampling tube on the convex surface. Unless the blade can be made so that the flow is properly distributed from both blade surfaces, the blade will not be usable and a calibration would be worthless. All the flow passed through the concave surface because the laminations were not constrained on the support member on this surface, and the laminations could not be forced together tightly enough to meter the cooling-air flow properly. On the convex surface, the laminations pressed together very tightly and would not allow the air to pass through. The convex surface was not impermeable, but so little restriction existed on the concave surface that pressure inside the blade could not be made high enough to force the air through the convex surface.

If the laminations had been attached to the support member by a brazing or welding operation, the coolant flow distribution would probably have been improved. Obtaining the proper pressure drop with this type of construction would be difficult because of the many openings between the thin laminations. The Eaton Company felt that the easiest way to obtain higher pressure drops would be to increase the width of the laminations and thus reduce the number of openings. Wire-wound blades fulfilled this condition and also provided an easier method of fabrication. No further efforts were made therefore to improve the flow characteristics of the sheet-metal laminated blade.

Wire-Wound Blades

Average flow rates. - The results of the calibration of the total flow rates for the wire-wound blades are presented in figure 6. The ordinate of the plot is a function of the coolant density at discharge pressure and temperature times the pressure drop in pounds per square inch, and the abscissa is the average flow rate per unit area for the entire blade. Calibrations were made for the knurled-wire blade with and without the slotted plate (fig. 3) and for the unknurled-wire blade without the slotted plate in the blade base. Figure 6 shows that the data for all three cases fell on a single straight line. The equation for the flow was

$$\frac{(\Delta p_a)p_{a,o}}{T_a} = 0.00163\left(\frac{w_a}{A} \times 10^4\right)^{1.72} \tag{1}$$

The fact that the data for the knurled-wire and the unknurled-wire blade fell on the same line is purely a coincidence, but the fact that the data with and without the slotted plate in the blade base fell on the same line does indicate that the plate had no effect on the coolant flow rates. This result was to be expected because the area of the two slots was far greater than the combined areas of the metering orifices at the blade root.

The pressure drop in the knurled blade occurred primarily across the metering orifices, whereas the pressure drop in the unknurled blade occurred across the wire at the blade surface. The pressure drop for a knurled-wire blade without the metering orifices would therefore be less than for an unknurled-wire blade for the same air-flow quantities. Metering of the air at the blade surface instead of at the blade root is preferable in a gas-turbine application because there are substantial pressure gradients around turbine blades in both the chordwise and the spanwise direction. The pressure drop through the blade wall must be high enough so that, by use of varying restrictions around the blade in the blade wall, the desired coolant flow distribution on the blade surfaces can be obtained. If the restriction is at the blade base instead of at the blade wall, almost all of the coolant will flow through the part of the blade where the local pressure on the outside surface is the lowest, which would result in nonuniform blade cooling.

The coolant flow rates for two porous specimens with a thickness of 0.120 inch are also shown in figure 6. The porosities of the porous specimens were 15 and 20 percent. Porosity is defined as unity minus the ratio of the porous-metal density to solid-metal density. The range between these two porous specimens had been tentatively set as the desired flow range corresponding to the pressure drops shown for the wire-wound blades. The coolant flow rate for the wire-wound blades approaches the range for the porous specimens at the higher flows, but this fact has little significance because the slopes of the lines are different. The slopes are different because the flow mechanisms for the porous metal and for the wire-wound blade are different. The flow-pressure relation for the wire blade is essentially the same as for an orifice, except that for an orifice the exponent in equation (1) would be 2. The pressure drop through a porous metal is due primarily to friction rather than momentum change. The equation relating the flow and the pressure drop is (reference 2):

$$\frac{p_{a,i}^{2}-p_{a,o}^{2}}{\tau} = \alpha 2RT_a\mu_a \frac{w_a}{A} + \beta \frac{2RT_a}{g}\left(\frac{w_a}{A}\right)^2 \qquad (2)$$

For low coolant flow rates, such as those shown in figure 6, the term involving w_a/A is much larger than the term involving $(w_a/A)^2$. By a simple analysis in which the second term on the right side of the equation is neglected, it will be found that the slope of the lines (fig. 6) for a porous metal should be less than for the wire-wound blade where the flow simulates that through an orifice.

Local flow rates. - Local flow rates were measured at a limited number of positions around the blade surfaces to obtain an approximate evaluation of the coolant flow distribution. The results of this investigation are shown in figure 7. Much greater scatter occurs in the data for local flows than for total flows because of the small quantities measured and also because of the roughness of the blade surfaces which made intimate contact between the blade surface and the sampling probe difficult to attain.

For the unknurled-wire blade, there was no significant trend in the data. The flow rates were approximately the same on both the concave and the convex surface. The data at the leading edge were inconclusive, but the flow rate at that location may have been almost 50 percent lower than at other locations. On the knurled-wire blade, the leading-edge flow was much higher than at the other parts of the blade because metering orifices were installed at the blade base purposely to direct more cooling air to the leading and trailing edges. The undesirability of this arrangement has already been discussed.

The data in figure 7 may at first appear inconsistent with those shown in figure 6 because figure 7 shows smaller local flow rates for the unknurled-wire blade than for the knurled-wire blade. This apparent inconsistency arose because representative locations for measuring the local flow rates on the blade were not chosen. At the midchord section of the unknurled-wire blade, the flow rates were much higher than at the midchord of the knurled-wire blade owing to the addition of metering orifices on the knurled-wire blade. The flow rates at these locations are not shown. The total average flows per unit of surface area for both blades are actually the same.

Results of the limited local flow calibrations indicate that the wire-wound blades are superior to the sheet-metal laminated blade in coolant flow distribution.

Required Flow Rates for Gas-Turbine Blades

A very brief analysis was made to determine at least approximately whether the flow rates and pressure drops encountered for the wire-wound blades would be suitable for gas-turbine operation. This analysis was made only for sea-level conditions at rated engine speed.

It was assumed that equation (1) was valid for densities other than those of the calibration and that, if the wires on the blades were pushed closer together, the exponent would remain at a value of 1.72 and only the constant would change. The velocity distribution for a typical turbine blade at sea level and rated engine speed is shown in figure 8. The coolant supply pressure, which is the compressor discharge pressure minus an allowance for losses, is also shown. The mean pressures for the calculations were assumed to be 34 pounds per square inch on the pressure surface and 15 pounds per square inch on the suction surface. The desired coolant flow rate was assumed to be 0.00169 pound per second per square inch for both blade surfaces. This flow rate was based on an engine gas flow of 73 pounds per second for a turbine having 54 blades with 16 square inches of surface area per blade and a ratio of coolant flow to gas flow of 0.02, which is probably adequate for this type of blade cooling. The coolant temperature was assumed to be 960° R, which is the compressor discharge temperature plus an allowance of 100° F for heating in the turbine disk. With the pressures, temperature, and coolant flow assumed, the constants for the equation

$$\frac{(\Delta p_a)p_{a,o}}{T_a} = C\left(\frac{w_a}{A} \times 10^4\right)^{1.72} \tag{3}$$

are 0.00571 and 0.00481 for the pressure and suction surfaces of the blade, respectively. The required pressure lines thus calculated are shown in figure 6. The required pressure drops are from 3 to $3\frac{1}{2}$ times as great as those obtained for the wire-wound blades. These results indicate that the wires on the blades would have to be squeezed together more tightly to make the blade satisfy coolant-flow requirements.

If the original blades were used in an engine, the supply pressures necessary to give the proper coolant flow would be 40 pounds per square inch for the pressure surface and 28.5 pounds per square inch for the suction surface. These supply pressures are less than the local pressure at the leading edge of the blade and, if used, would result in flow from the gas stream into the blade at that location and the blade would approach gas temperature.

Because the local pressure is high at the leading edge of turbine blades, less restriction of the flow will be required there than at any other place on the blade. The heat-transfer rates are also high at the leading edge and the coolant flow rates should be further increased. The average restriction for the blades investigated was approximately correct for the leading edge, but a greater restriction is required for the rest of the blade.

SUMMARY OF RESULTS

The results of this coolant-flow calibration of three simulated porous gas-turbine blades are as follows:

1. The sheet-metal laminated blade in its present form was entirely unsatisfactory for gas-turbine application because of extremely poor coolant flow distribution over the blade surface.

2. The pressure drops for the wire-wound blades were too low for gas-turbine application. The wires would have to be squeezed closer together to make the blades suitable.

3. The metering of the coolant flow should take place at the blade surface rather than at the blade base in order to obtain proper coolant distribution in a spanwise direction.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 8, 1951.

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2. Green, Leon, Jr., and Duwez, Pol: The Permeability of Porous Iron. Prog. Rep. No. 4-85, Jet Prop. Lab., C.I.T., Feb. 9, 1949. (Ordnance Dept. Contract No. W-04-200-ORD-453.)

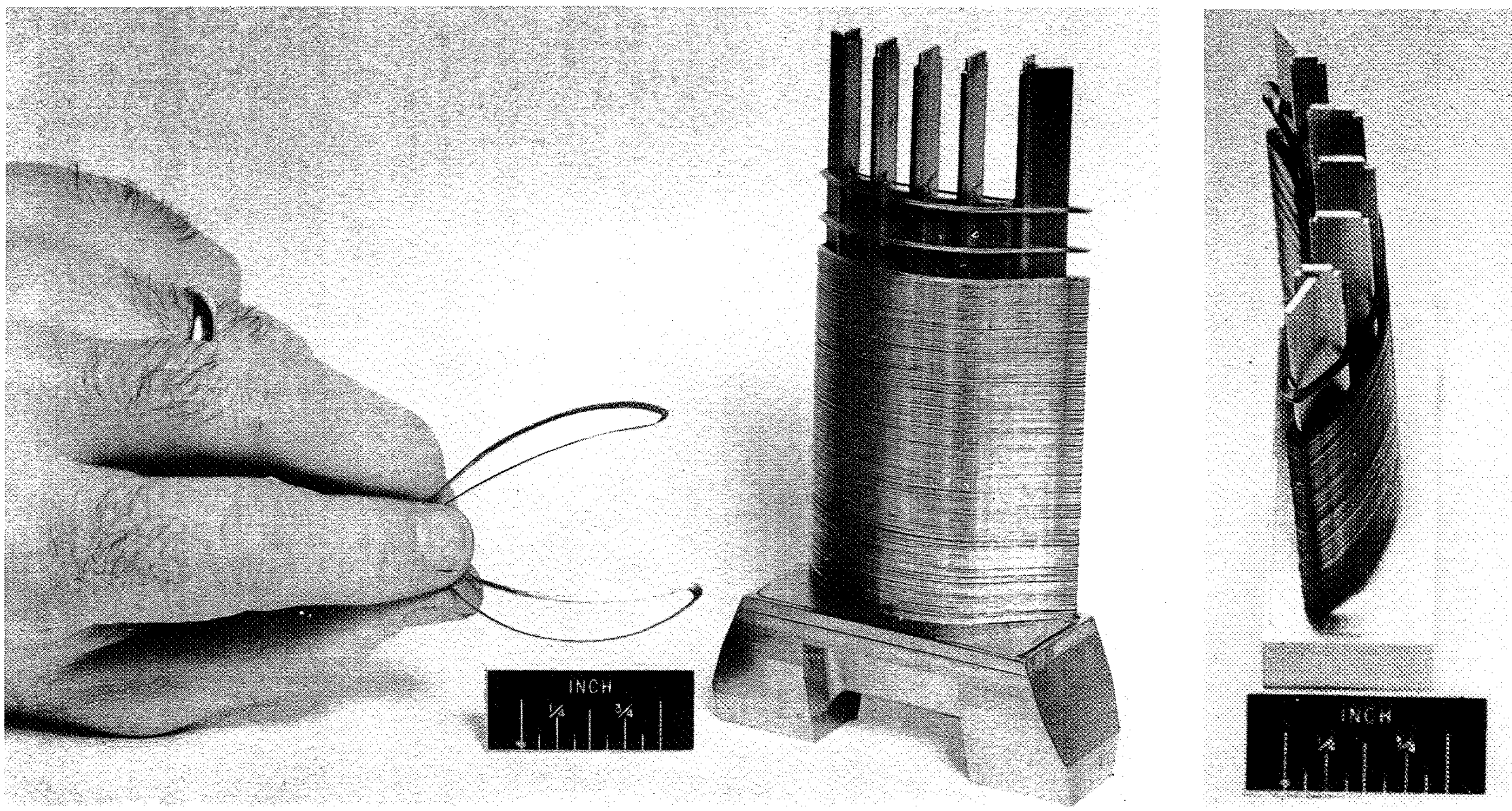

Figure 1. - Sheet-metal laminated turbine blade.

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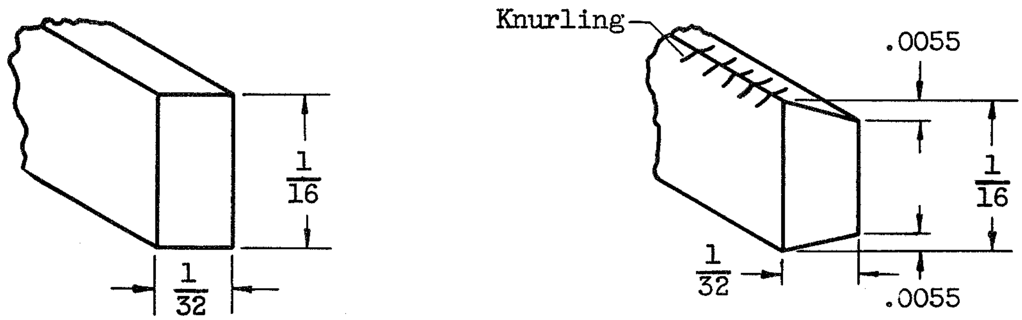
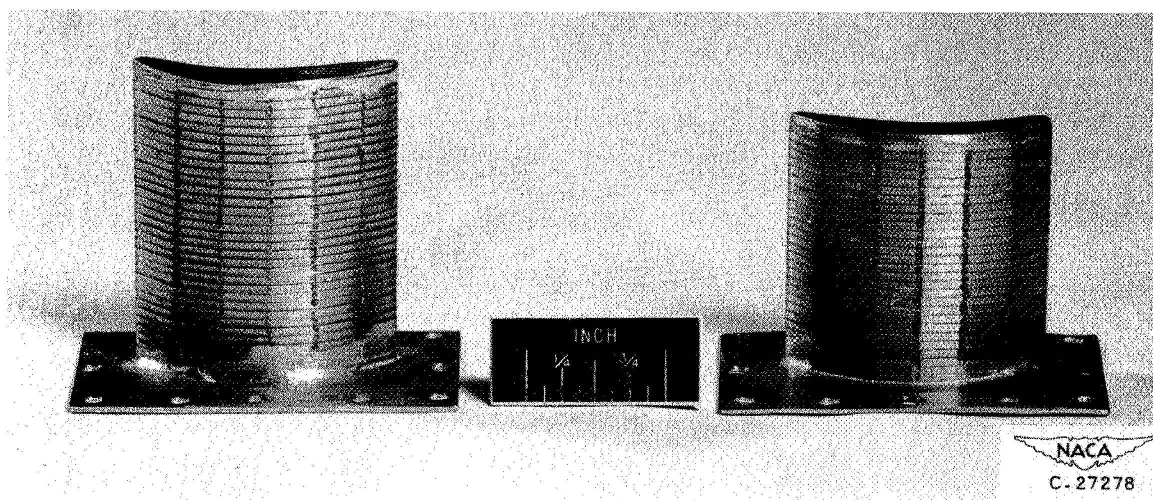


Unknurled

Knurled

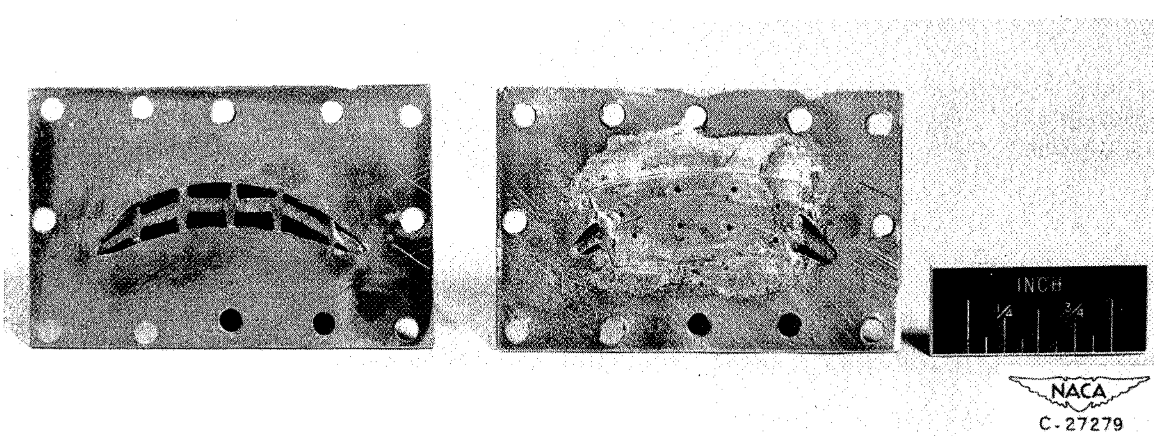
(a) Wire cross-sections.



Unknurled

Knurled

(b) Blade shells.



Unknurled

Knurled

(c) Blade bases.

Figure 2. - Wire-wound turbine blade shells.

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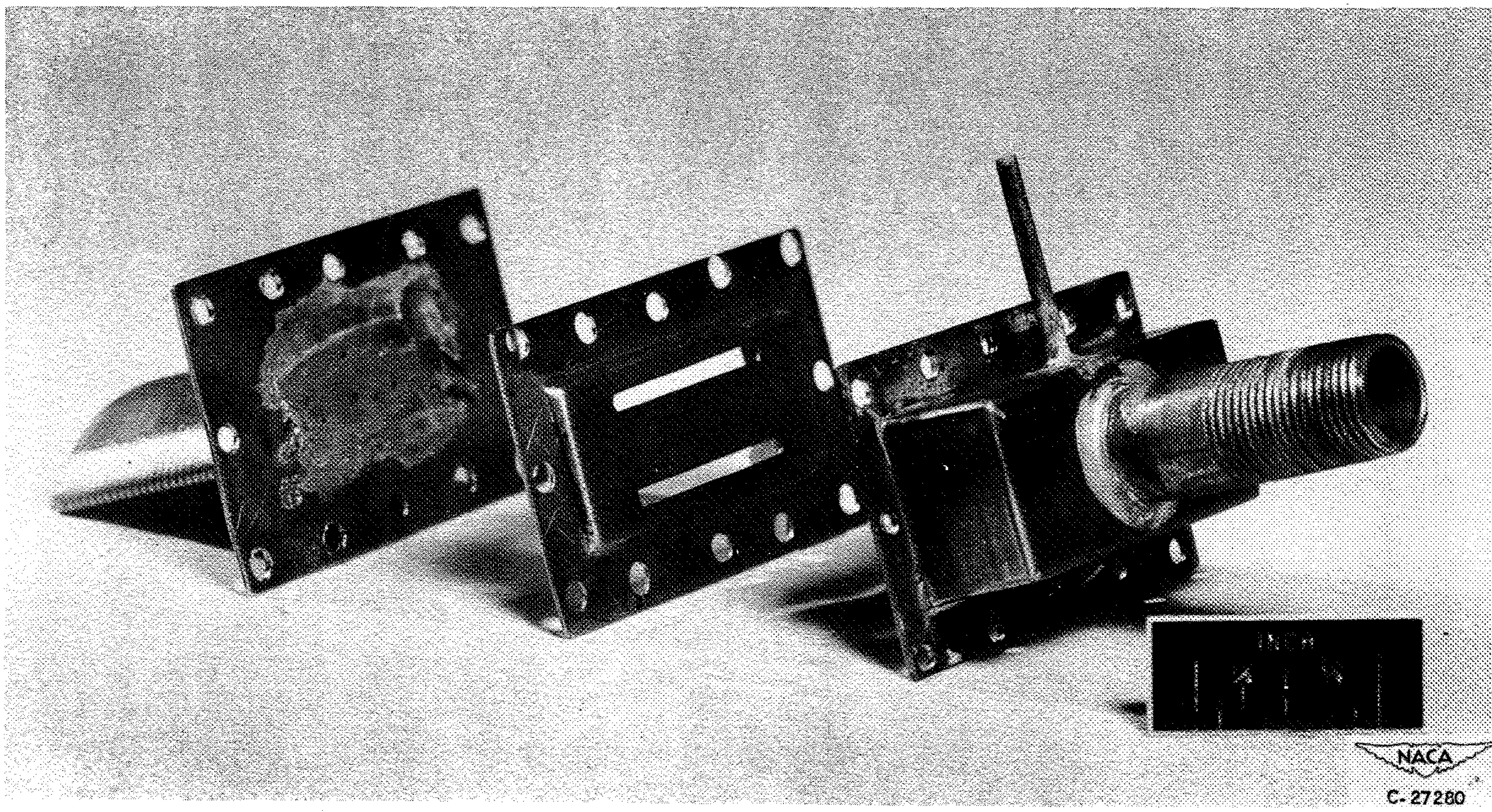

Figure 3. - Exploded view of wire-wound blade test assembly.

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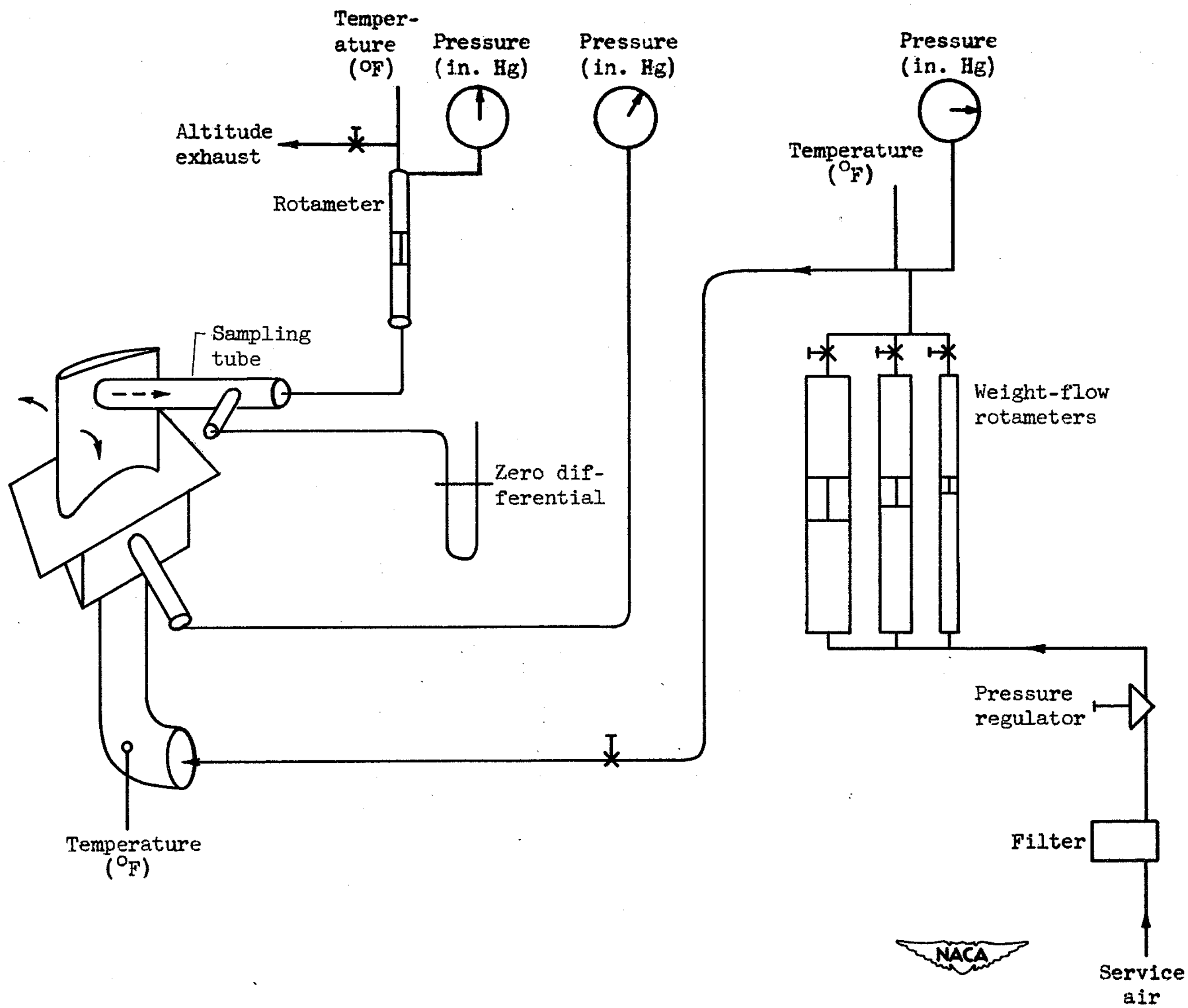

Figure 4. - Schematic sketch of flow-calibration apparatus.

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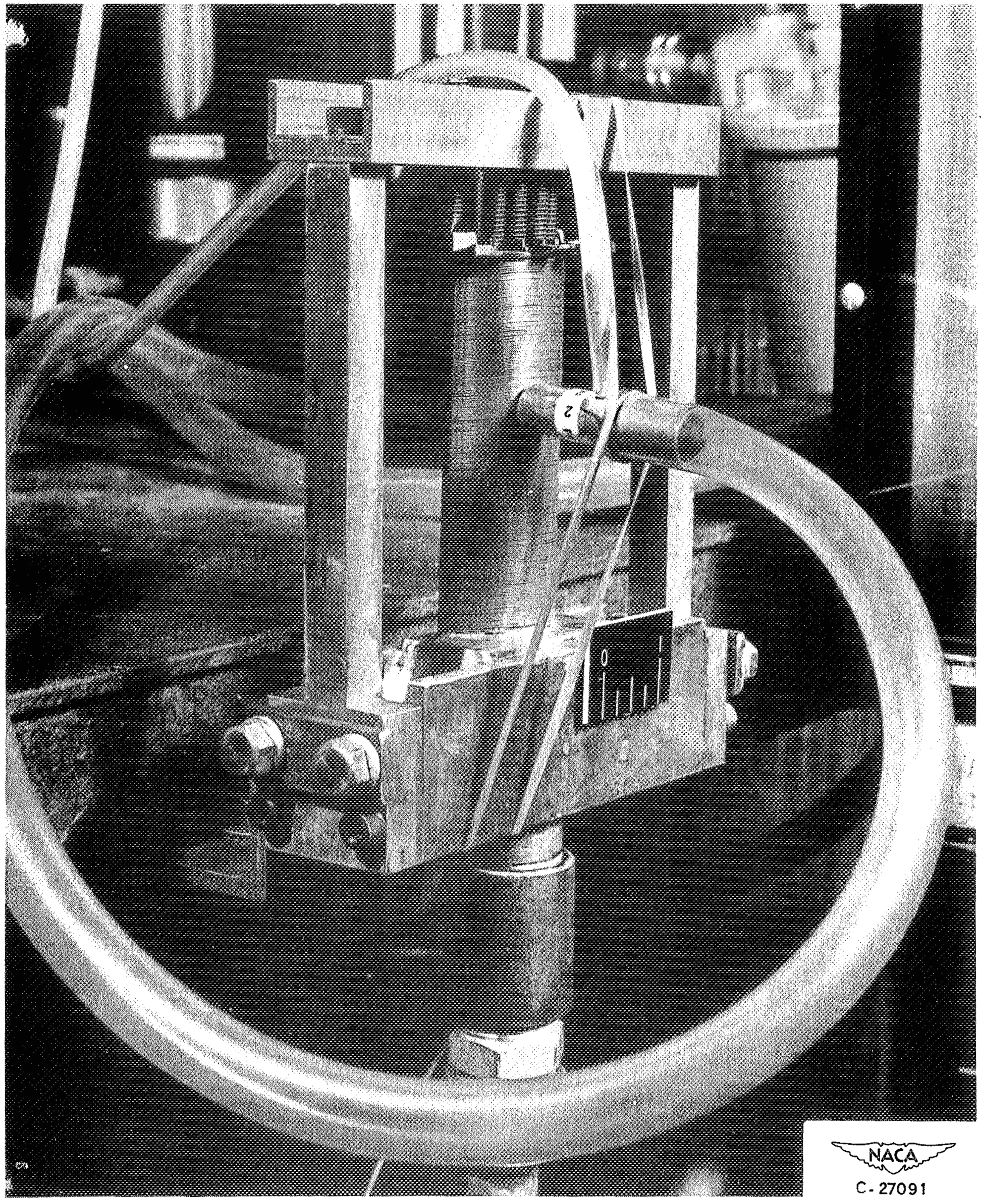

Figure 5. - Sampling probe for measuring local coolant flow rates.

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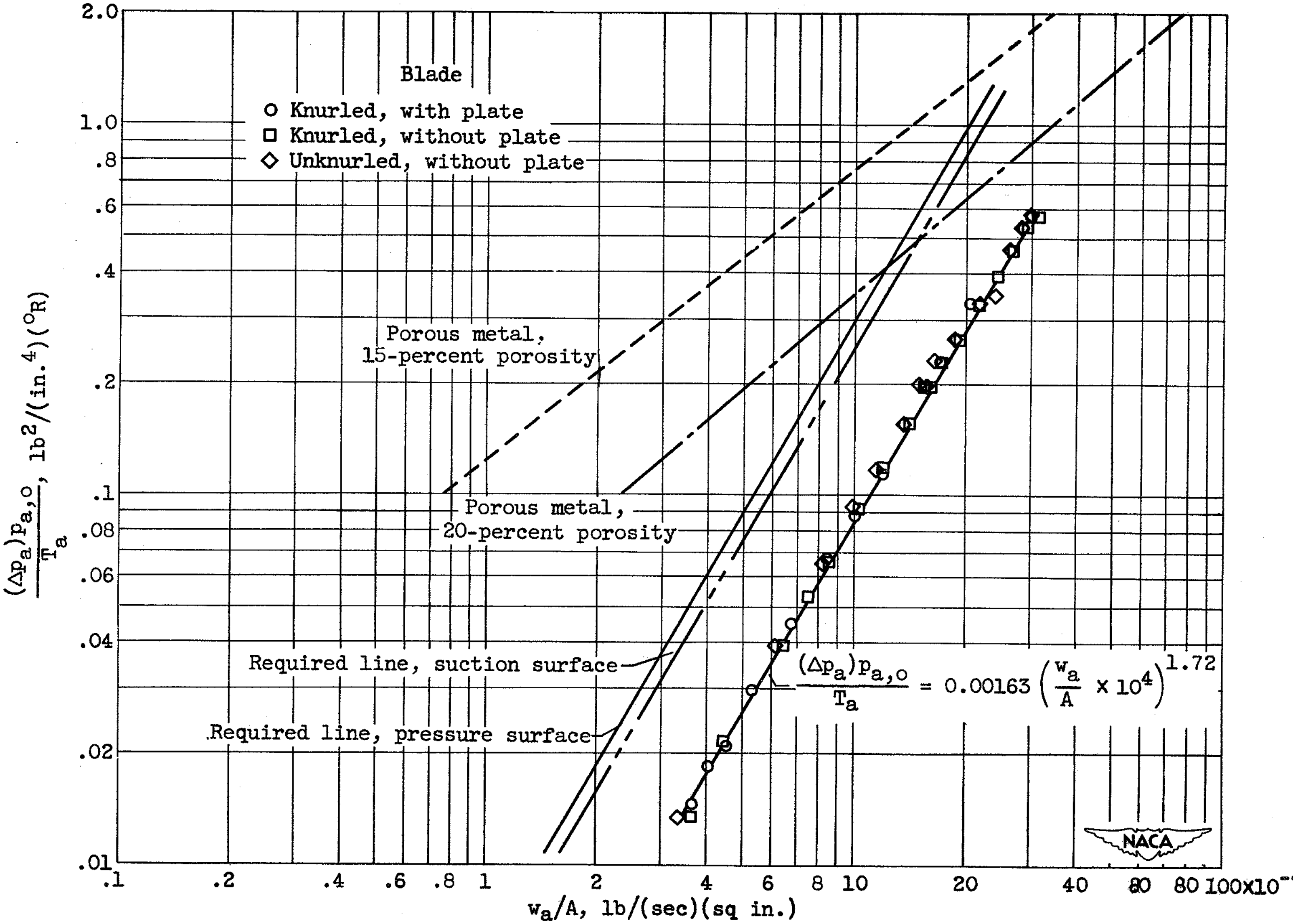
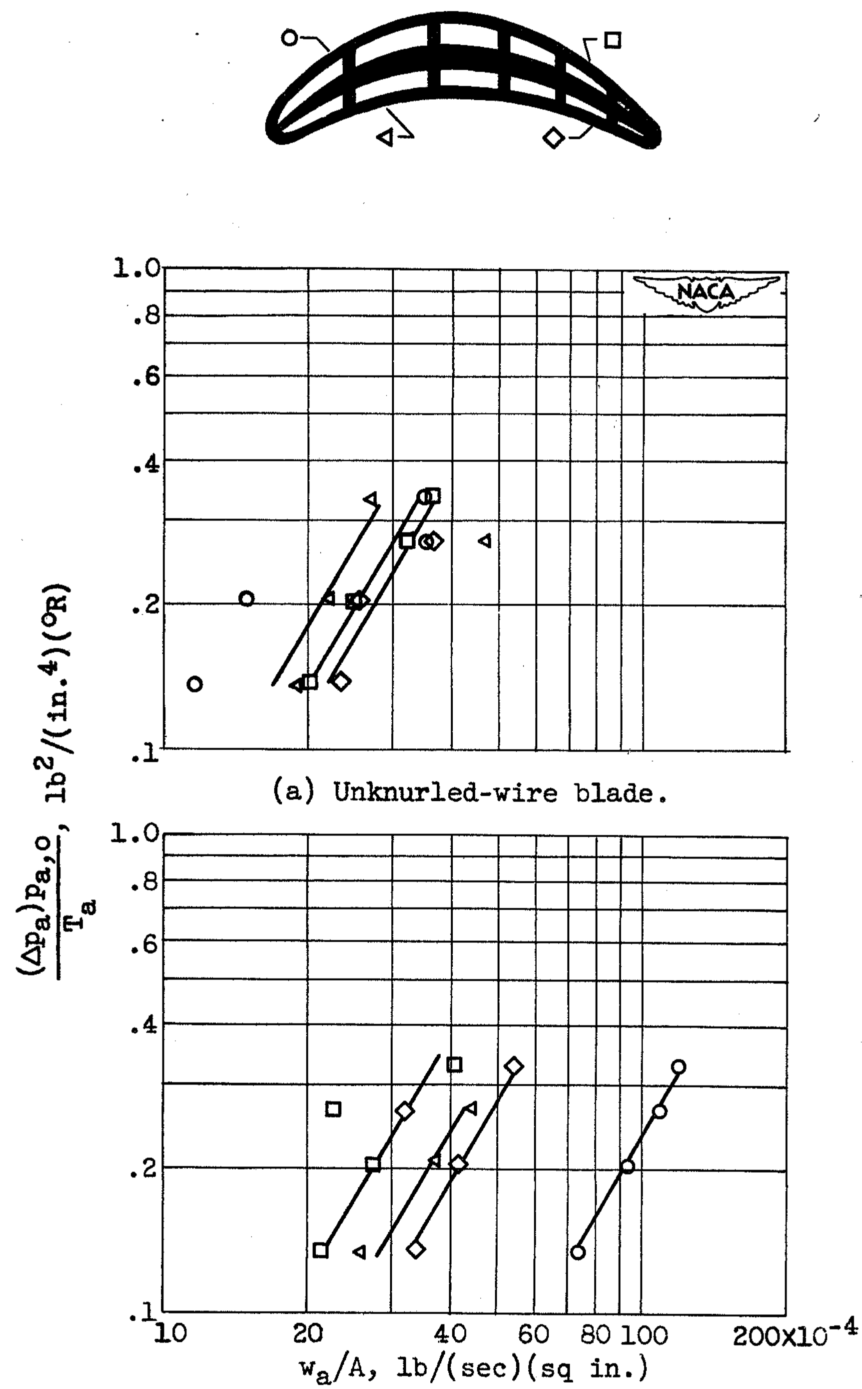


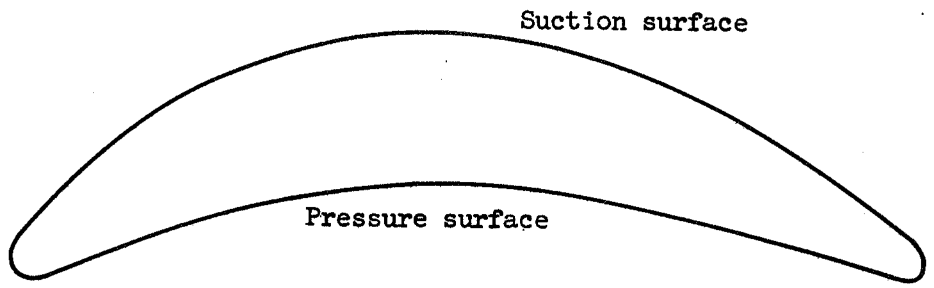
Figure 6. - Average coolant flow rates for wire-wound blades.



(a) Unknurled-wire blade.

(b) Knurled-wire blade.

Figure 7. - Local coolant flow rates for knurled-wire and unknurled-wire blades.



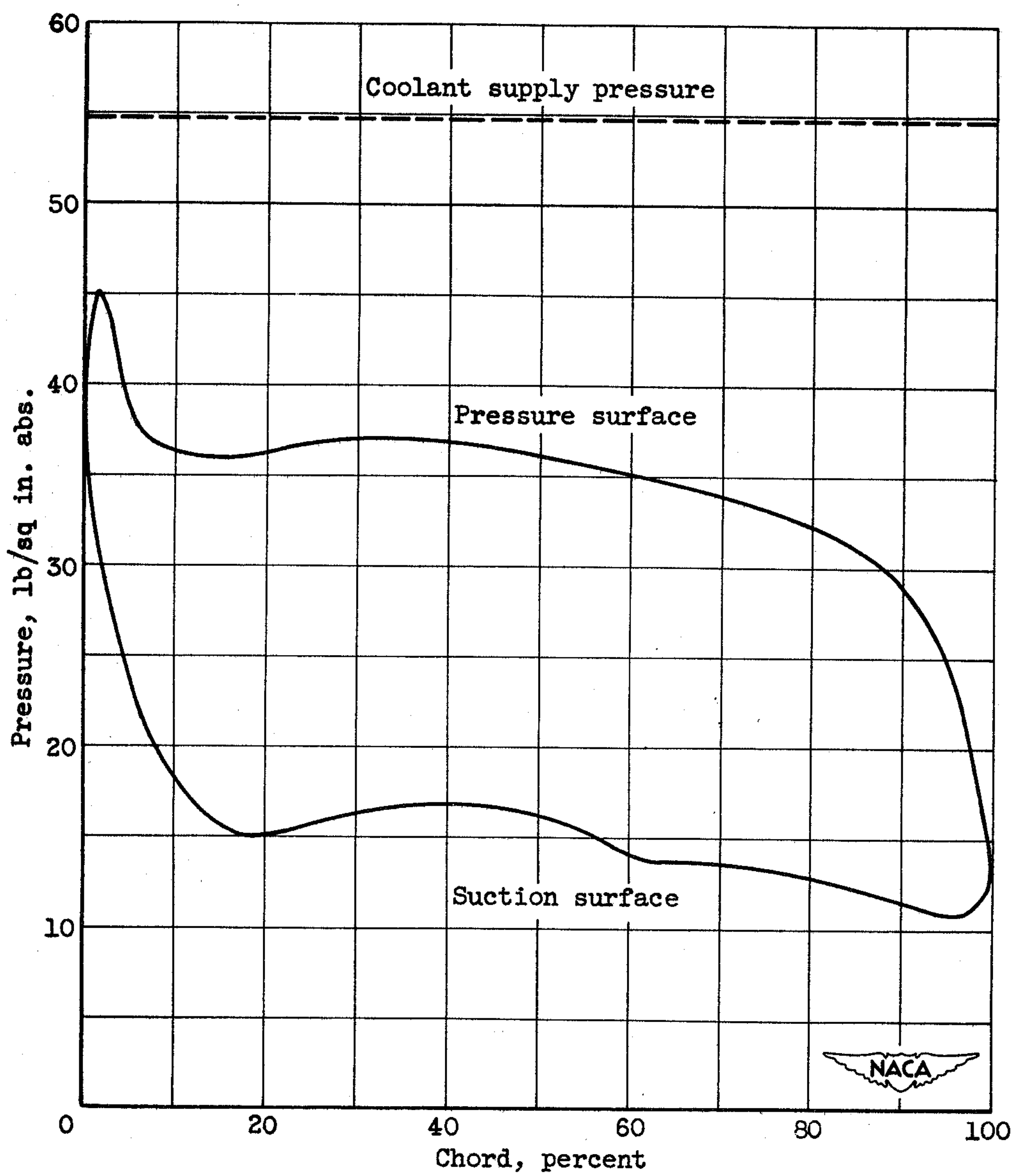


Figure 8. - Pressure distribution around typical turbine blade at sea level and rated engine speed.